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METEOROID SIMULATION USING LASERS

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O. K. Hudson

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ABSTRACT

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This is a brief discussion of the current state of laser technology relative to meteoroid simulation. It shows that efforts up to this time are inadequate, but that a carefully designed experiment with this objective in view, and employing essentially off-the-shelf apparatus, may enable one to find the laws of similarity and of correlation between both kinds of high-energy impact phenomena. Some recent literature is surveyed and references provided.

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I. INTRODUCTION

For some time, the author has advocated the use of lasers for simulating hypervelocity impacts such as those made by meteoroids. This suggestion is based on the following observations:

(1) An examination of the available data indicates that meteoroids will have velocities between about 10 km/sec and 80 km/sec.

(2) From hypervelocity data (taken at speeds on the order of 10 km/sec or less) and from meteoroid flux curves due largely to Whipple [1] (this work is based on optical, radar, satellite microphones, zodiacal, solar flare, and gegenschein light measurements), it is thought that meteoroids whose masses lie between 10^{-10} and 10^{-4} gm will be sufficiently energetic and frequent to constitute a hazard to space missions.

(3) An experimental study of impact phenomena of particles with precisely known mass, size, and velocity in the velocity regime above 10 km/sec has not been achieved. The Russian literature implies that they are equally ignorant on this subject [2].

II. STATEMENT OF THE PROBLEM

The problem of meteoroid simulation may be approached by considering the physical characteristics which a typical meteoroid might possess. Let us assume that a representative meteoroid has a mass of 10^{-5} gm and a speed of 40 km/sec, then the kinetic energy is easily found to be about 8 joules. If the particle were a solid calcium sphere (density 1.55 gm/cm^3), then the cross-sectional area would be 6×10^{-3} mm^2.

Assuming a constant deceleration in the distance of the particle diameter, the energy is deposited in less than one nanosecond.

To simulate the meteoroid just described, a laser must deposit 8 joules in one nanosecond or less into an area of 6×10^{-3} mm^2. The power required is 8000 MW.

III. ON THE VALIDITY OF SIMULATION

Spectroscopic measurements indicate that about nine out of ten meteoroids are stoney; it is for this reason that calcium was chosen as a representative composition.

When the kinetic energy of 8 joules is distributed among the total number of molecules present in the meteoroid, one finds 3 eV/molecule. Since this is of the order of the binding energy in the material, one may assume that the meteoroid will behave on impact as a loosely associated collection of individual molecules (i.e., the strength of the material is unimportant).

A particularly simple theory has been deduced by K.P. Stanyukovich [3] to predict the momentum transferred to the target by an impacting particle at hypervelocities. His theory, slightly extended by the author, yields the result that the momentum transferred to the target is the sum of the incident particle momentum plus a constant times the kinetic energy of the incident particle. Momentum multiplication, which is a physical interpretation of this constant, has been measured in a few isolated instances. At the author's suggestion, GM Defense Research Laboratory of Santa Barbara, California plotted some of their momentum data against the Stanyukovich Theory and found excellent agreement for the few data points shown below. This work, done on contract no. NAS 8-1118, was reported recently at the 7th Hypervelocity Impact Symposium.

For 1100-0 aluminum as both target and projectile, it was found:

velocity (km/sec)	4.00	5.43	5.95	7.11
constant (sec/km)	0.160	0.163	0.153	0.170

There is a considerable scarcity of this type of data; it is clearly an area in which more measurements should be made.

The implication of Stanyukovich's theory (and its possible verification) is that the momentum transferred to the target is more dependent upon the incident energy per unit area than on the momentum per unit area deposited by the particle. It is upon this assumption that lasers may simulate meteoroid impacts, since, of course, the laser beam is made up of radiant energy only.

IV. LASER EXPERIMENTS

The brief account from literature dealing with this subject, which follows, is not to be construed as an exhaustive bibliography.

The earliest paper is by Askar'yan and Moroz [4]. The authors specifically suggest the use of lasers for cutting metal, accelerating particles to high velocities, and producing ultrasonic waves in solids. It is a theoretical paper in which recoil pressure, time of evaporation, and energy transfer are computed.

In July 1963, several papers appeared in the literature, the first of which concerned work done by White [5] prior to July 1962, and was primarily related to the production of elastic waves in metals generated by pulsed electron beams; however, in one experiment a laser was used to generate the elastic wave. The work (although not regarded as conclusive) indicated that the elastic wave was not generated by the radiation pressure associated with the laser beam.

Ready [6] , whose work was done prior to April 1963, studied phenomena involved in the vaporization caused by absorption of a high-powered laser beam on an opaque surface. The apparatus used was a Kerr Cell, Q-switched laser focused by a simple lens. The target was a carbon block in air. He reports a 30-MW beam focused to an area of about 3×10^{-1} mm^2 , the energy being about 90% emitted in 0.3×10^{-7} sec. There was a 1.2×10^{-7}-second delay between the initiation of the laser pulse and the maximum brightness of the plume whose wave front moves at about 20 km/sec.

Work was done by Howe prior to May 1963 and reported in September 1963 [7]. The target material used was identified as National Carbon Co. polycrystalline type CCH synthetic graphite. When the laser beam (produced by a 3×10^3-joule discharge) was focused on this material, a blue-white mushroom-shaped jet over 1 cm in length resulted. In addition to the highly luminous jet, photographs revealed bright streaks resulting from ejection of incandescent particles. The jet formed normal to the surface of the target regardless of the incident angle of the laser beam, and each jet was accompanied by the formation of a small crater in the target having a volume of the order of 10^{-6} cm^3 . Vaporization of this amount of material to ground state C atoms would require 0.1 joule [8] . Spectral studies of the light emitted from the graphite jet in air were made with the aid of a 2 m grating instrument. These studies showed the presence of strong CN and C_2 emission with only a trace of blackbody continuum. No lines were observed which were not attributable to these two species. Particularly obvious was the absence of the carbon 2479 Å line. From a theoretical treatment of the spectral emission, Howe concludes that temperatures of the order of 1000° K were attained.

Time resolution studies revealed that the C_2 emission began simultaneously with the rise of the laser pulse, whereas the CN emission was delayed some 15 to 75 microseconds, decreasing with increasing laser power. Apart from this, both signals showed similar behavior in reaching a peak value some 30 microseconds before the laser power began to fall. The laser output pulse was found to last for some 100 to 300 microseconds, depending on the flash energy; the 3000-joule discharge produced a measured single pulse output of about 1 joule at 6943 Å. The output beam was filtered to remove stray pump light, and brought to a focus by a single lens of 6-cm focal length. The observed diameter of the focal spot was about 0.3 mm, which corresponds to a light intensity of some 10 MW/cm^2. An indication of the jet velocity was obtained by measuring the delay between onset of laser action and peak emission at a known distance from the target surface. Values were found to lie in the range of 9 to 30 km/sec, the smaller values resulting from the lower laser powers.

In December 1963, work done at GE prior to July 1963 by Norton, et al., in the use of lasers for hole cutting was reported [9]. This paper is especially important since it describes what is probably the best experimental technique for obtaining small beam area on the target material. Laser-drilled holes made in razor blades with simple lenses are greater than 10^{-1} mm diameter [10]. A form of Abbé resolution limit formula was used by Shawlow [11] to describe the smallest focused spot that can be produced by a plane-coherent laser beam. He concluded that d, which is the spot size minimum imposed by diffraction, is of the order of the wavelength λ.

$$d = L \frac{\lambda}{a}$$

where

L = focal length

a = aperture

λ = 6943 Å for a ruby laser

By using a reflecting objective lens (A. O. No. 1200), Norton was able to produce controlled hole diameters ranging from 5×10^{-3} mm to 50×10^{-3} mm in tungsten and molybdenum sheet whose thicknesses ranged from 20 to 50×10^{-3} mm. The holes were conical, and there was some sputtering of molten metal around them. The optical system has withstood repeated ruby laser blasts as high as 2 joules. Millisecond bursts in excess of 4 joules cause deterioration of the first reflecting surface in the optical system. Unfortunately, no further information is given concerning the laser pulse shape.

The most recently published paper (Ames Research Center [12]). concerns work with momentum transfer and cratering effects produced by lasers. Neuman's laser contained 0.3 joule of energy, and its width at half maximum was 0.5×10^{-7} second. Unfortunately, he neither describes his optical system, nor does he mention his focused image size, except to say that he defocuses to a spot size of 18 mm for some experiments. Most of the data are qualitative, e.g., there is qualitative evidence that the momentum transfer is proportional to the square root of the incident energy density.

V. INTERPRETATION OF DATA

It is clear that all of the data mentioned here fall short of the requirements in one way or another.

White [5] indicates that radiation pressure is not the source of the elastic waves observed in the target during these laser experiments. This implies that the absorbed energy is therefore the source of the elastic energy.

Ready [6] used energies which were small, areas which were too large, and a pulse duration which was too long. Unfortunately, his work was done in air, and the chemical reactions with the atmosphere prevented a critical examination of the craters produced in the experiment.

Howe [7] used energies which were too small and areas which were too large. His pulse duration was far too long and even though he measured a crater volume, it is doubtful that the data have significance for meteoroid simulation purposes. His work does indicate that angle of incidence of the laser beam, at least within limits, is not an important factor in the energy deposition. His spectrographic measurements tend to show that the ejecta, at least at time of ejection, is in the form of excited target molecules rather than atoms.

Norton has shown how the appropriate area of energy deposition may be achieved, but his energies were too small and his pulse duration was far too long.

Neuman's laser power was too small and his pulse duration was too long. His areas were undefined, but were probably far too large. He does find evidence that target momentum is somehow proportional to incident energy density.

VI. CONCLUSIONS

The feasibility of using lasers to simulate meteoroids has not been adequately demonstrated. Available information concerning off-the-shelf apparatus indicates that the current state-of-the-art is an order of magnitude away from satisfactory simulation of impacts whose craters would be subject to convincing measurement.

It is concluded that, until either microcrater analysis techniques are perfected or more powerful lasers of shorter pulse duration are available, lasers cannot satisfactorily meet NASA requirements in this area.

On the other hand, acoustic signals resulting from the impact of small objects having meteoritic velocities and extremely small kinetic energy can be detected. Using acoustic signals rather than crater analysis, it may be possible that careful measurements with well-controlled laser pulses, and equally careful measurements with hypervelocity particles, will enable one to find laws of similarity and of correlation between both kinds of high energy impact phenomena while using currently available apparatus.

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This document has also been reviewed and approved for technical accuracy.

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